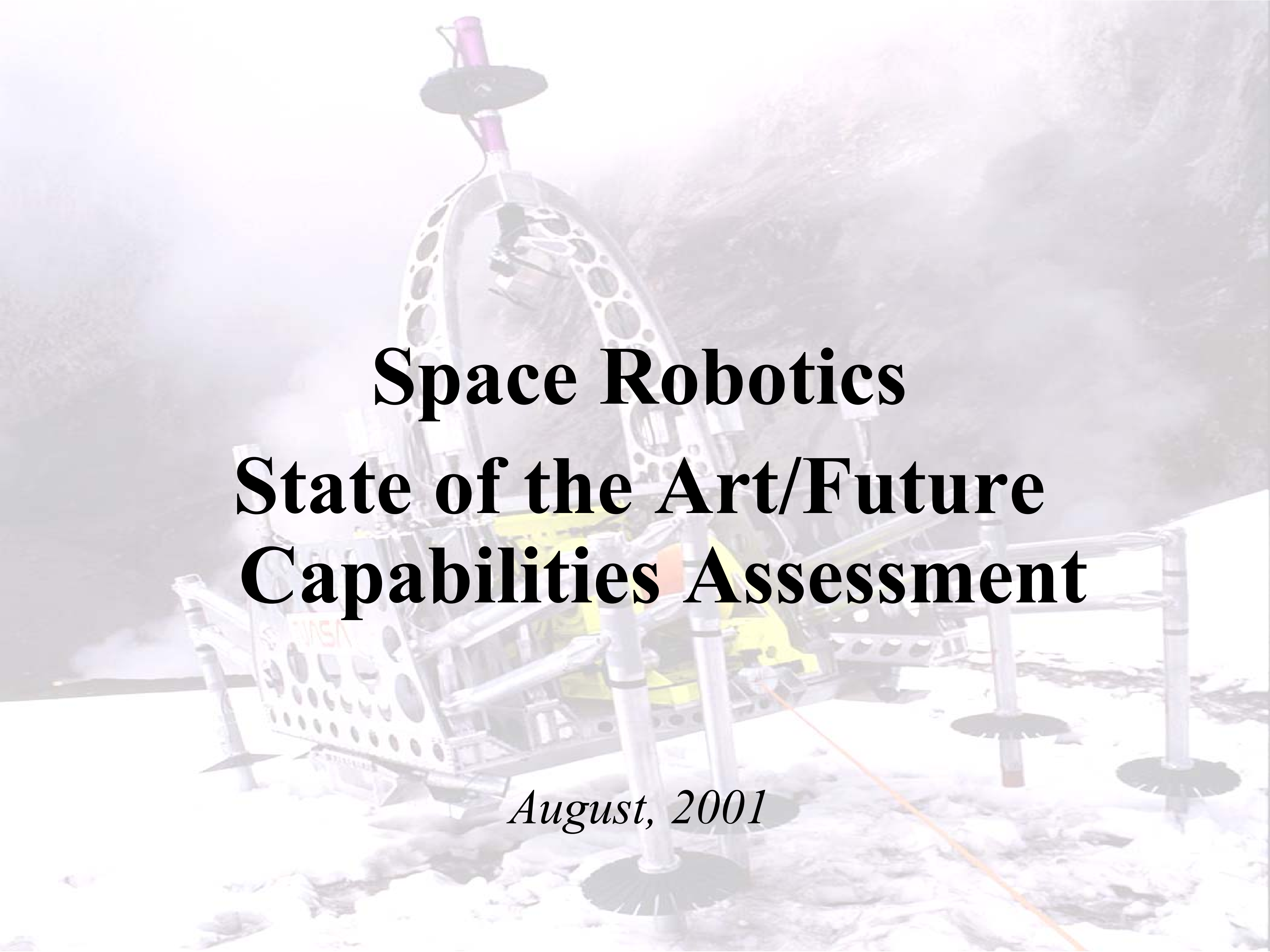


Space Robotics
State of the Art/Future Capabilities Assessment

August, 2001

Outline

- Overview/Motivation
- Approach
- Mission Scenarios
- Functionalities
  - Mars Exploration Scenario
  - In-Space Assembly Scenario
  - Projections and Breakthroughs
- Open Questions, Schedule and Future Work

Ideal Process

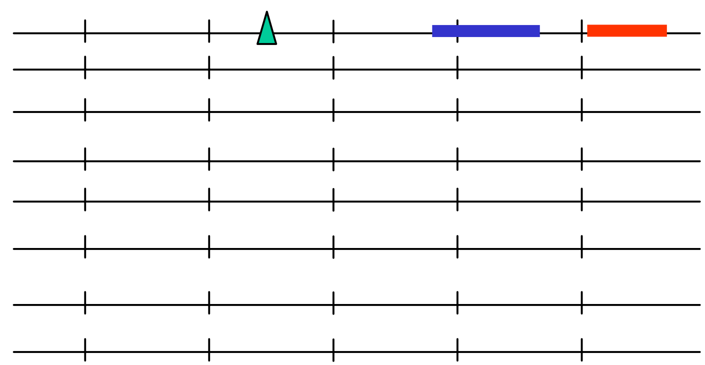
Science Objectives → Desired Measurements → Mission Concepts → Required Capabilities → Robotics Technology

Space Robotics assessment and prediction

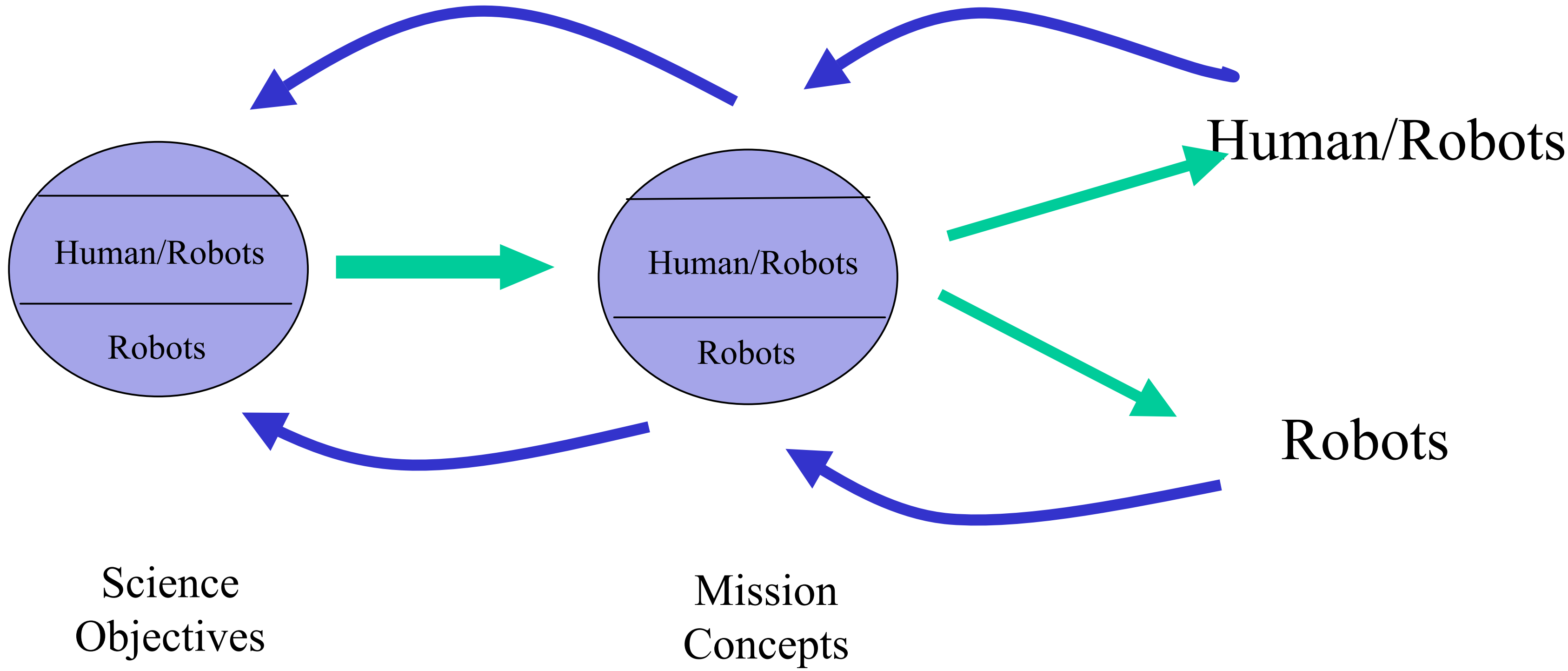
Planetary Exploration
- Mobility
  - Autonomy
  - Mechanism
- Science Operations
  - Science Perception, Planning and Execution
  - Sample handling and manipulation
  - …

In-space Assembly, inspection and Maintenance

…

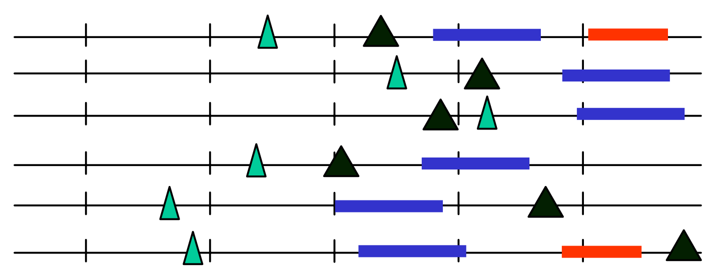


Why Humans process?



Planetary Exploration
- Mobility
  - Autonomy
  - Mechanism
- Science Operations
  - Science Perception, Planning and Execution
  - Sample handling and manipulation
  - …

…



Human and Robot Exploration

- Human/Robot Working Group of the NEXT (formerly Decadal Planning Team) is chartered with determining the optimal split between human and robot space exploration
- Several studies are being funded
  - Assessment of space robotic state-of-the-art and projections
  - Knowledge capture from human space explorers
  - Assessment of EVA technology state-of-the-art and projections
  - Assessment of human centered computing state-of-the-art and projections
  - Experimental tests of human vs. robot performance
- All studies will be combined into integrated report to the OMB

Ideal outcome of our study

Products:

- Briefing package that can be used to communicate current and expected space robotic capabilities.
- Roadmaps for technology investment required to achieve these capabilities.
- Written report detailing the results of the study.

Desired impact:

- Begin forming a community focusing on the issue of joint human/robotic exploration.
- Generate increased advocacy within the agency for both robotic capabilities and the benefit of joint human/robotic interaction.
- A few “good ideas” regarding technology demonstration missions that can garner support within the agency.

Benefit to Space Robotics Technologists

- "Snapshot" of where we are as a community
- Set of metrics with which to rate accomplishments
  - Community cooperation to build metrics
- Identification and explanation of key capabilities necessary for space robotics
- Identification of NASA space robotic needs

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Methodology

- How do we measure space robotic capabilities?
  - What is important?
    - Functionalities, e.g., mobility
  - How do you measure it?
    - Qualitative metrics, e.g., terrain capability
    - Quantitative metrics, e.g., distance traveled
- What is the state of the art?
  - Fielded robotic systems, e.g., Sojourner, Nomad
  - Laboratory demonstrations
- What is the future?
  - Projections, bottlenecks and roadmaps

Community input

- Site visits and interviews
- Written contributions
- Workshop in FY02

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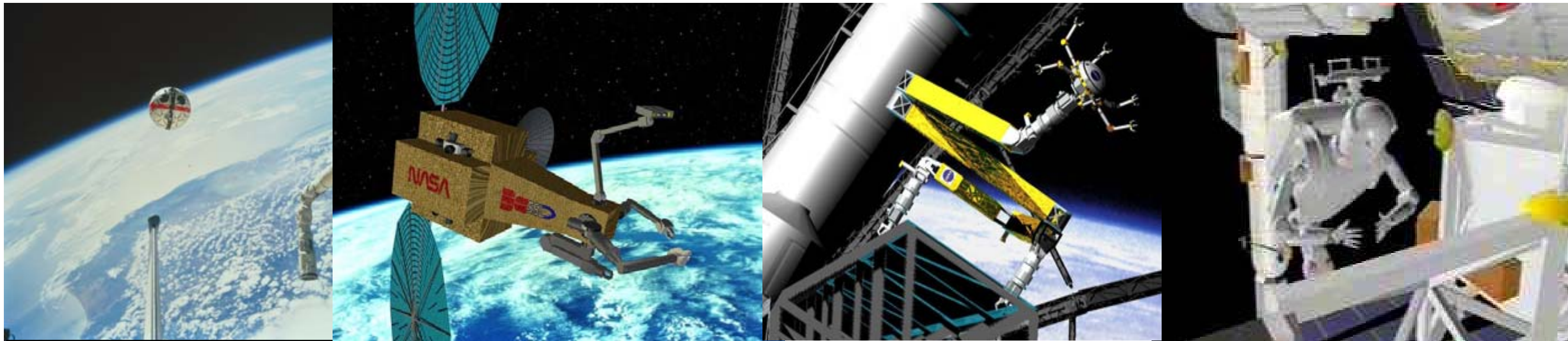
Mission Scenarios

	Planetary Surface Missions	In-Space Missions
Exploration	X	
Work Operations		X

In-Space Assembly, Inspection, and Maintenance



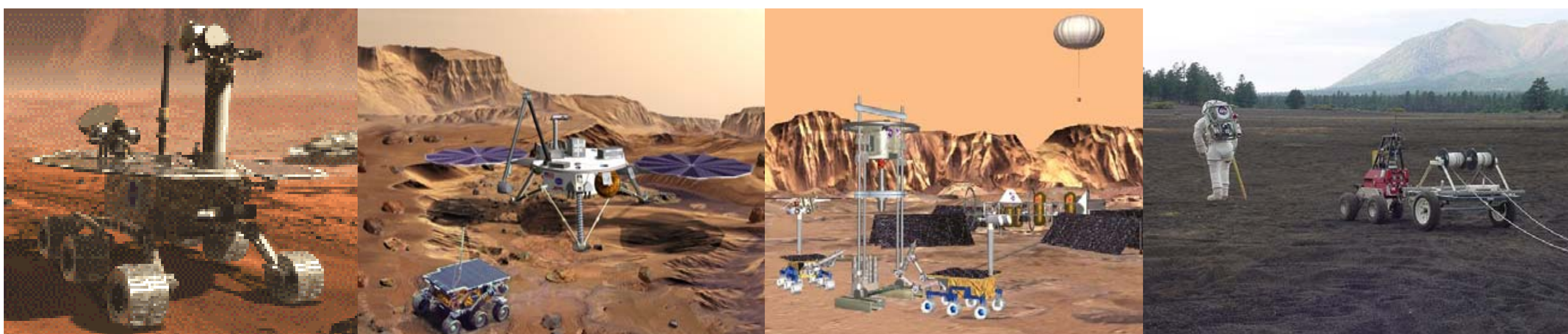
Inspection

Pre-planned maintenance

Assembly of large structures

Troubleshoot and repair

Planetary Surface Exploration



Long range reconnaisance

In depth site survey

Sample acquisition and analysis

Joint Human/Robotic

Outline

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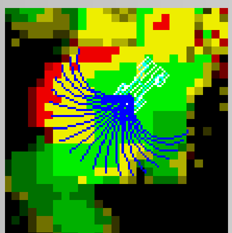
Space Robotic Functionalities

- Derived from mission scenario requirements
- Provide means for organizing and evaluating various robotic technologies
- Deliberately limited:
  - Space robotics, not robotics
  - Two mission scenarios
- Motivated by existing space robotics research

Mars Surface Exploration Functionalities

Mobility



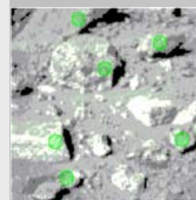
Mobility Autonomy

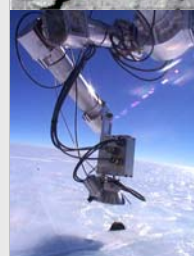
Terrain assessment, path planning, visual servoing

Mobility Mechanism

Extreme terrain access, energy efficiency

Science Operations





Perception, Planning, Execution

On-board and ground tools; data analysis, target selection, operations planning and execution

Sample Manipulation

Position sensors, collect and process samples

Multi-Agent Interaction

Robot-Robot Interaction

Communication, architecture, distributed and coordinated tasks

Human-Robot Interaction

Tele-operation to human supervision; robot/EVA astronaut teams

In-Space Assembly, Inspection, and Maintenance Functionalities

Manipulation

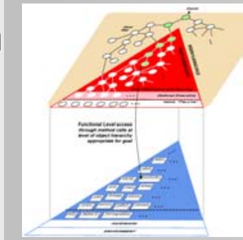
Mobility and Gross Manipulation

Move self and other massive elements; path planning, coverage patterns

Fine Manipulation

Manipulate small objects and tools; hand-eye coordination; fine motion planning

Higher-Level Autonomy



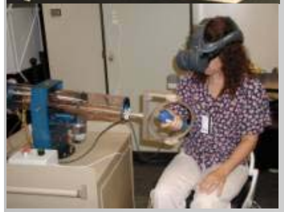
Planning and Execution

On-board and ground tools; architecture; task planning; reacting to unexpected events

Multi-Agent Interaction

Robot-Robot Interaction

Communication, architecture, distributed and coordinated tasks



Human-Robot Interaction

Tele-operation to human supervision; robot/EVA astronaut teams

Metrics

Capability measures

- Qualitative Scaling
  - Precise definitions
  - Generalize to many systems
- Quantitative Measures
  - Resist temptation to use many easy to measure but uninformative numbers
  - Cannot be reported for some fielded systems, but will hopefully "set the bar" for future reporting of results

What is the current state-of-art?

- Evaluate ***relevant*** systems according to metrics
  - Related to scenarios
  - Path to space deployment
  - *Not* interested in a historical retrospective
  - **Space readiness metrics**
    - Defines how close a robotic system is to being deployed in a space environment
    - Size, mass, power, computing, etc.
- Infer performance envelope

Future Forecast

- State-of-Art in +5, +10 years, Fielded or not possible in 20 years.
- Range of projections
  - Minimal support
  - Strong support
- Use metrics
- Identify capabilities which require breakthroughs, but do *not* forecast when or how each breakthrough will occur

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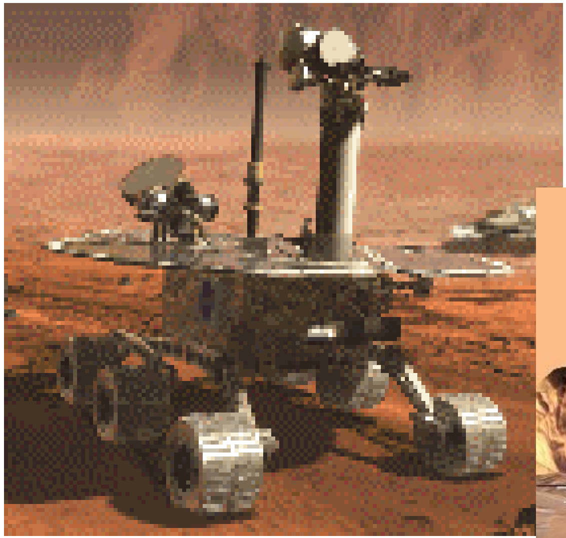
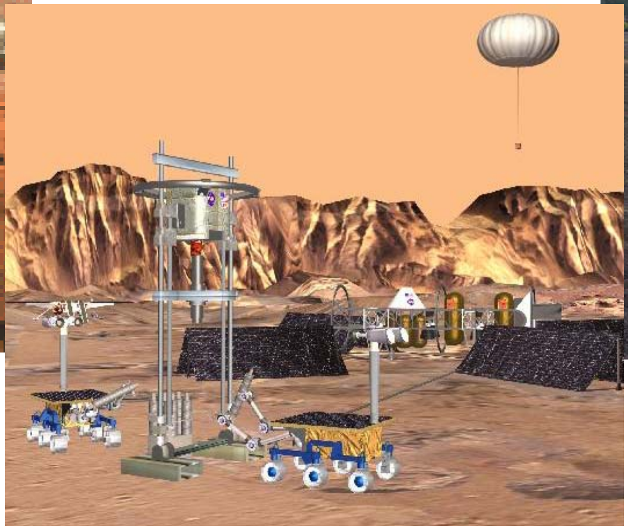
Mars Surface Exploration Scenario



Surface Reconnaissance

Robotic Science Outpost and Sub-Surface Exploration



Human Exploration Assistance

Increasing infrastructure →

Surface Mobility Autonomy and Mobility Mechanism

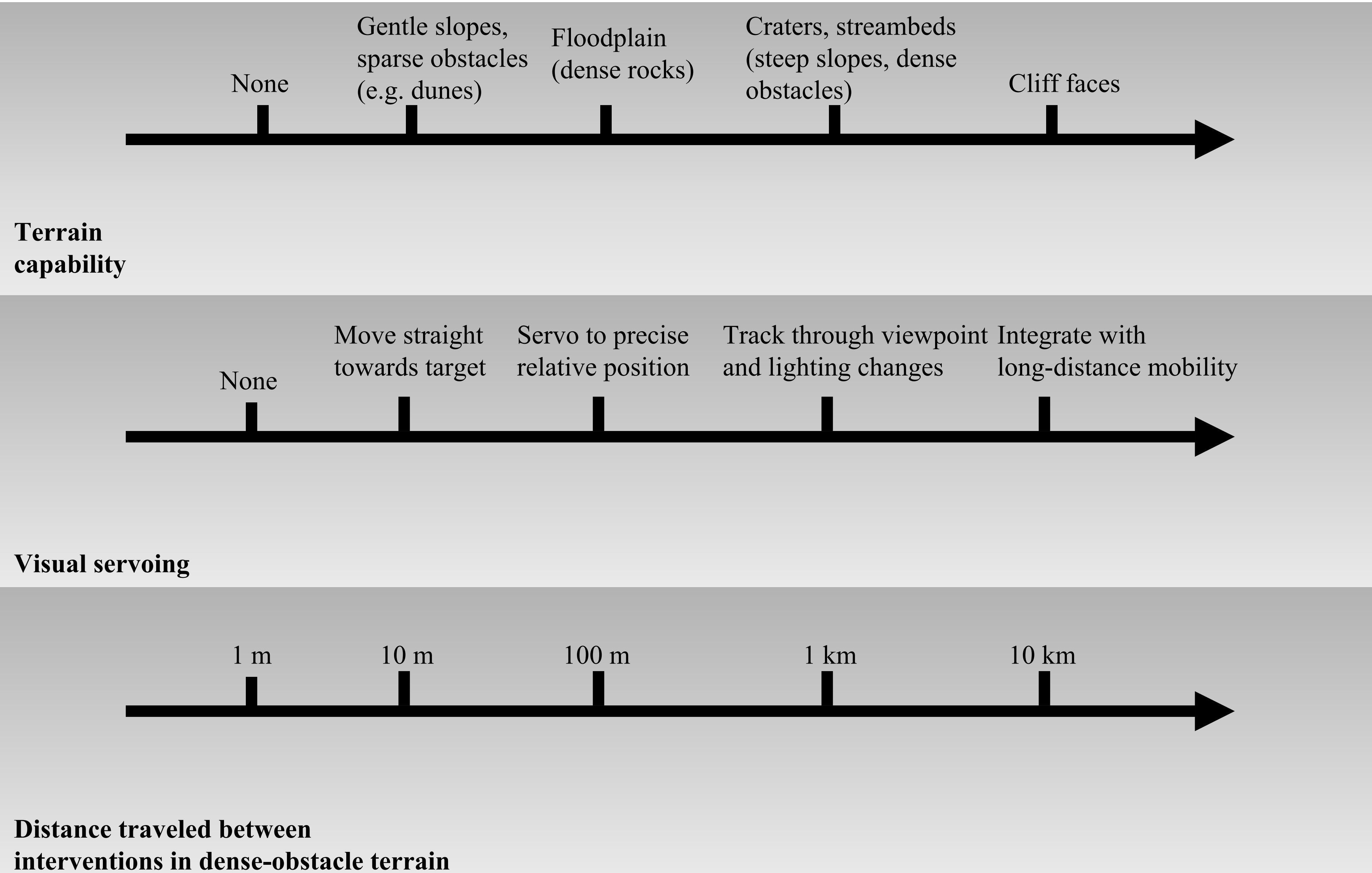
Mobility Autonomy:

- Self localization
- Goal location
- Path and motion planning
- Obstacle avoidance

Mobility Mechanism:

- Physical implementation of the mobility system
- Wheels, legs, tracks or other mechanisms to move robot over terrain

Surface Mobility Metrics

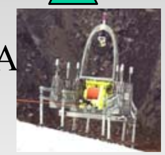


Surface Mobility State-of-Art

Terrain capability

None — Gentle slopes, sparse obstacles (e.g. dunes) — Floodplain (dense rocks) — Craters, streambeds (steep slopes, dense obstacles) — Cliff faces

Flight SOA
Sojourner



Fielded SOA
Dante

Visual servoing

None — Move straight towards target — Servo to precise relative position — Track through viewpoint and lighting changes — Integrate with long-distance mobility

Flight SOA

Fielded SOA
Rocky 7 [Nesnas et. al.]

Distance traveled between interventions in dense-obstacle terrain

1 m — 10 m — 100 m — 1 km — 10 km

Flight SOA
Sojourner

Fielded SOA
Rocky 7 [Laubach et. al.]

Surface Mobility Relevant Systems

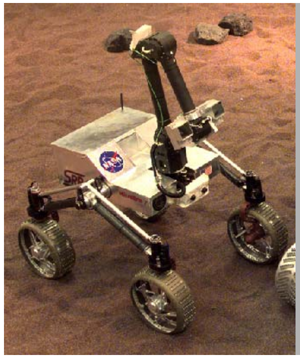
Hyperion

Health monitoring

Long traverses

Path planning

Sample-Return Rover (SRR)



Mechanical reconfiguration

Model-registration localization

Rendezvous with lander

Dante II

Extreme slope access

Gait planning

Other Systems

- Sojourner
- MER 2003
- Rocky 7
- Nomad
- Mars Autonomy Project
- Urban Reconnaissance Robot
- And more…

Example Space Readiness Metrics Table

Relevant Systems

Space Readiness Metrics

	Nomad	Rocky 7 Visual Servoing	Mars Autonomy Project	Rocky 7 Auton. Navigation	Urban Reconnaissance Robot
Mass and Size	0	3	3	3	2
Power	1	2	2	2	2
Computing	1	2	2	0	1
Test Conditions	2	2	2	2	1
Reliability	?	?	1	?	?
Space Qualified	0	2	2	2	0

Example Qualitative Metrics Table

Relevant Systems

Qualitative Metrics

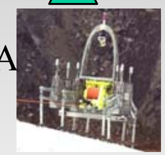
	Nomad	Rocky 7 Visual Servoing	Mars Autonomy Project	Sojourner	MER 2003	Lone Rovers	Robotic Science Outpost	Joint Human-Robot Exploration
Localization	1	1	1	1	1-3	1-3	3-4	3-4
Terrain Assessment	1	0	1	0	1-2	1-2	2-4	2-4
Mapping	3	0	3	1	2-3	2-3	2-4	2-4
Obstacle Avoidance	3	0	3	1	2-3	2-3	2-4	2-4
Path Planning	3	0	3	0	0-3	0-3	2-4	2-4
Visual Servoing	0	2	0	0	0-2	0-2	2-4	2-4

Surface Mobility State-of-Art

Terrain capability

None — Gentle slopes, sparse obstacles (e.g. dunes) — Floodplain (dense rocks) — Craters, streambeds (steep slopes, dense obstacles) — Cliff faces

Flight SOA
Sojourner



Fielded SOA
Dante

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Flight SOA

Fielded SOA
Rocky 7 [Nesnas et. al.]

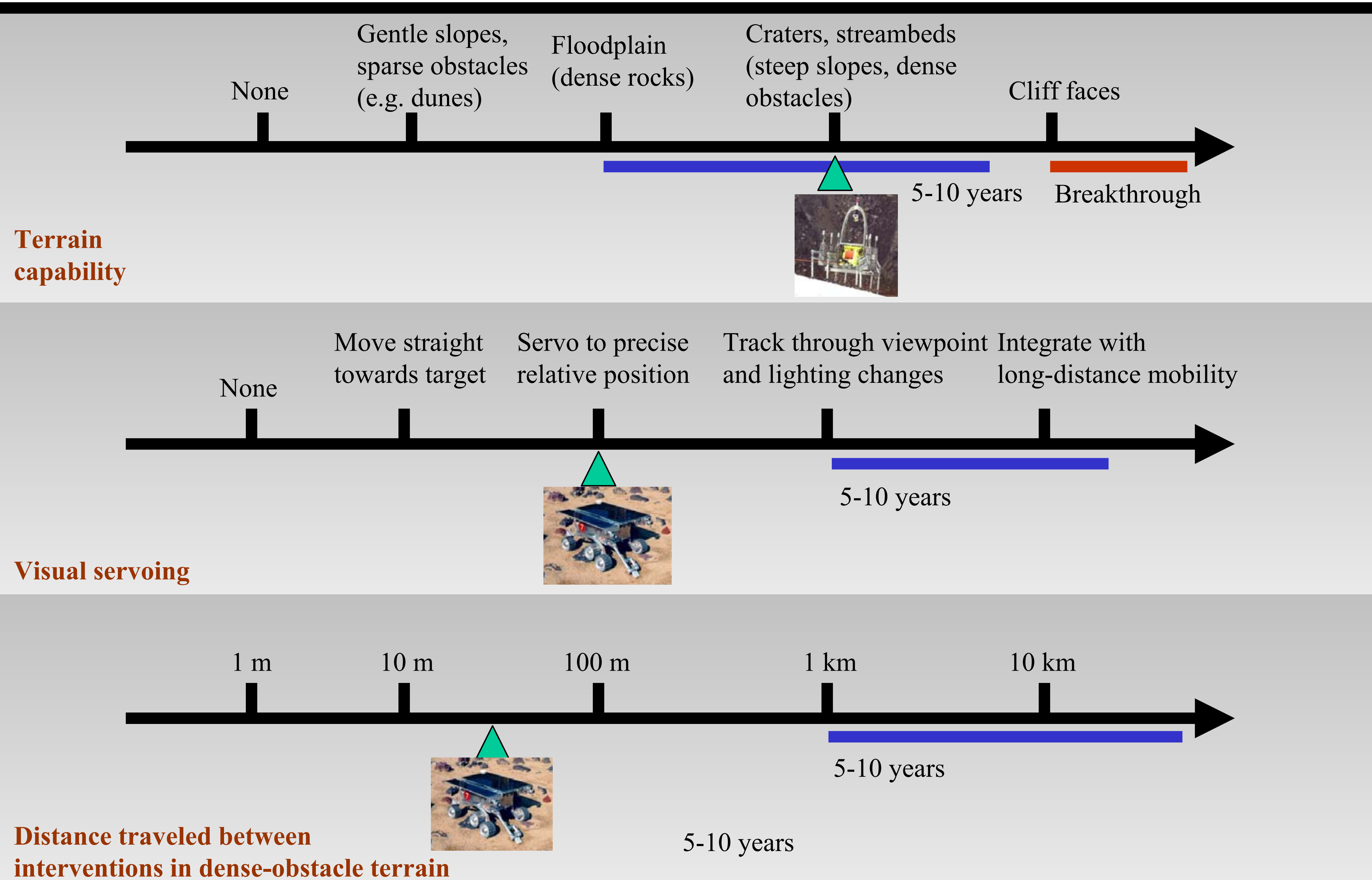
Distance traveled between interventions in dense-obstacle terrain

1 m — 10 m — 100 m — 1 km — 10 km

Flight SOA
Sojourner

Fielded SOA
Rocky 7 [Laubach et. al.]

Surface Mobility Projections



10 year Surface Mobility Claims

Terrain capability (mobility mechanism)

With minimal support:

- Sojourner-like mechanisms, increased mobility from larger size.
- 100 m between uplinks.

With strong support:

- Traversal of streambeds and craters.
- Tethered cliff explorers.
- 1 km between uplinks, 1000 km total.

***Breakthrough*: Advanced legged or hopping systems (no "robotic mountain goat")**

Visual servoing (mobility autonomy)

With minimal support:

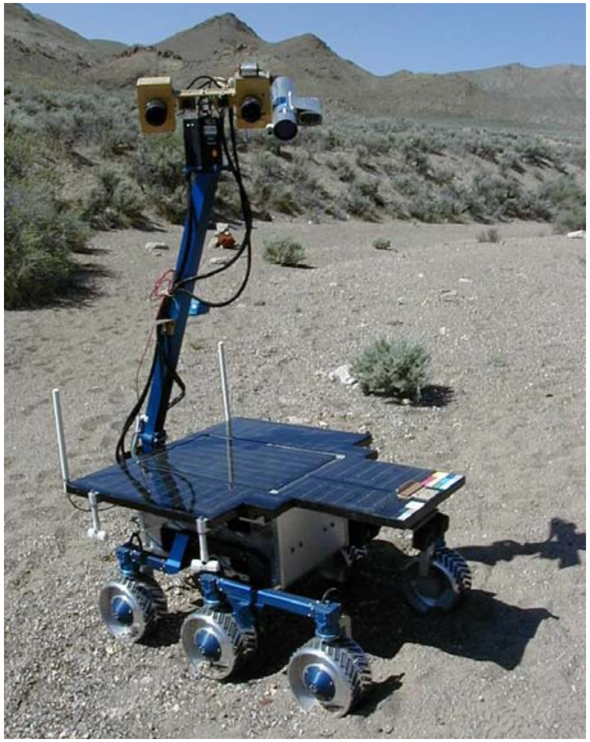
- Robust servoing to a target in view, with simple obstacle avoidance.

With strong support:

- Servoing to multiple widely separated targets in a single uplink
- Re-acquisition of lost targets

Surface Science Perception, Planning and Execution

- **Locate scientifically interesting targets and make relevant observations.**
- **Plan science tasks to be performed, taking into account constraints on the robots resources and the value of different science observations.**
- **Executing the plan using the robot and its instruments to collect relevant science data. Monitoring the state of the robot and its environment and reacting to changes.**



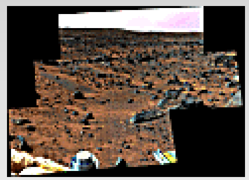
Science Perception, Planning and Execution METRICS

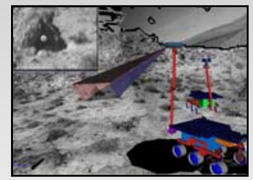
Ground science planning and understanding

Scientists request measurements to flight engineers who do planning

All planning & sequencing by scientists

- Raw data
- Derived 2D data products
- Terrain model, annotations
- Virtual presence



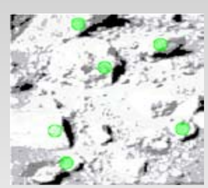


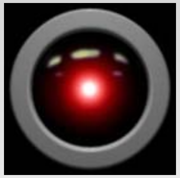
On-board science planning and execution

- None (tele-operation)
- Time stamped sequence
- Flexible time, contingencies
- Prioritized task list with constraints
- High level science goals

On-board science perception

- Return all data
- Return selected data
- Select targets
- Characterize site
- Recognize unforeseen scientific opportunities





Science Perception, Planning and Execution: State-of-Art

Scientists request measurements to flight engineers who do planning

All planning & sequencing by scientists

Raw data

Derived 2D data products

Terrain model, annotations

Virtual presence

Ground science planning and understanding

Flight SOA Sojourner

SOA: WITS, VIZ

None (tele-operation)

Time stamped sequence

Flexible time, contingencies

Prioritized task list with constraints

High level science goals

On-board science planning and execution

Surface Flight SOA

SOA Remote Agent

Return all data

Return selected data

Select targets

Characterize site

Recognize unforeseen scientific opportunities

On-board science perception

Flight SOA

Fielded SOA Nomad [2000]

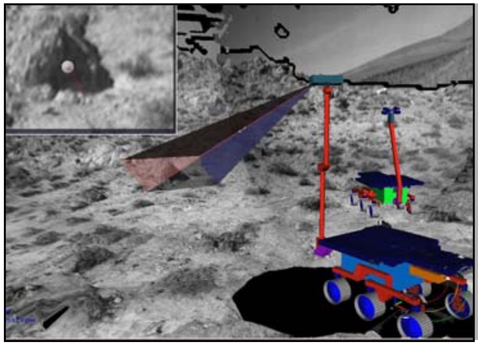
Science Perception, Planning & Execution Relevant Systems

Nomad 2000

Autonomous meteorite identification

Selects targets

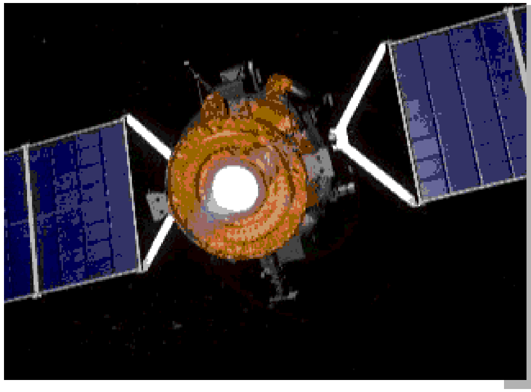
VIZ



Virtual environment for scientific visualization

Ground planning tool for scientists

DS1 / Remote Agent



Onboard planning, scheduling and execution of space-craft operations

Multiple goals; constraints between them, flexible duration.

Other Systems

- MER 2003 (WITS)
- GSOM software tools
- APGEN
- And more…

Science Perception, Planning and Execution: Forecasts

Scientists request measurements to flight engineers who do planning

All planning & sequencing by scientists

Raw data

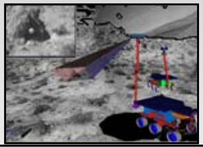
Derived 2D data products

Terrain model, annotations

Virtual presence

5-10 years

Ground science planning and understanding



None (tele-operation)

Time stamped sequence

Flexible time, contingencies

Prioritized task list with constraints

High level science goals

5-10 years

Breakthrough

On-board science planning and execution

Return all data

Return selected data

Select targets

Characterize site

Recognize unforeseen scientific opportunities

5-10 years

Breakthrough

On-board science perception

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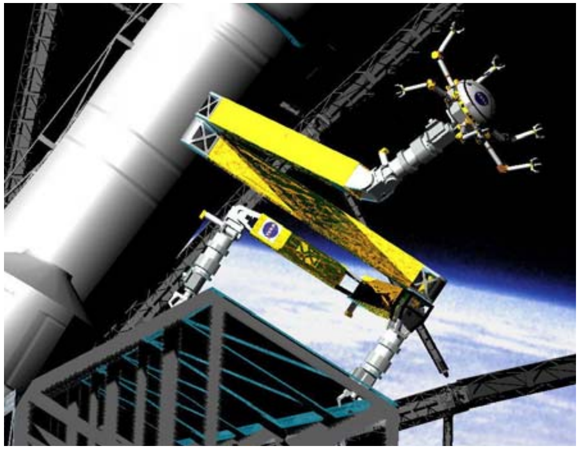
Space Assembly, Inspection and Maintenance Scenario

Inspection

Pre-planned maintenance



Assembly of large structures and troubleshooting

Decreasing human presence? →

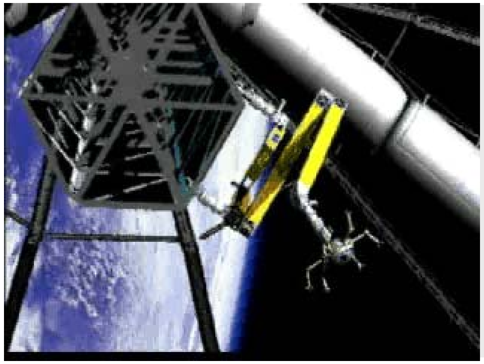
Increasing task complexity →

In-Space Mobility and Gross Manipulation Relevant Systems

AERCam Sprint

- Freeflyer
- Tele-operated w/auto stop rotate
- Carried two cameras

Skyworker



- Transport of objects
- Motion planning
- Low-energy climb on structure

Shuttle RMS

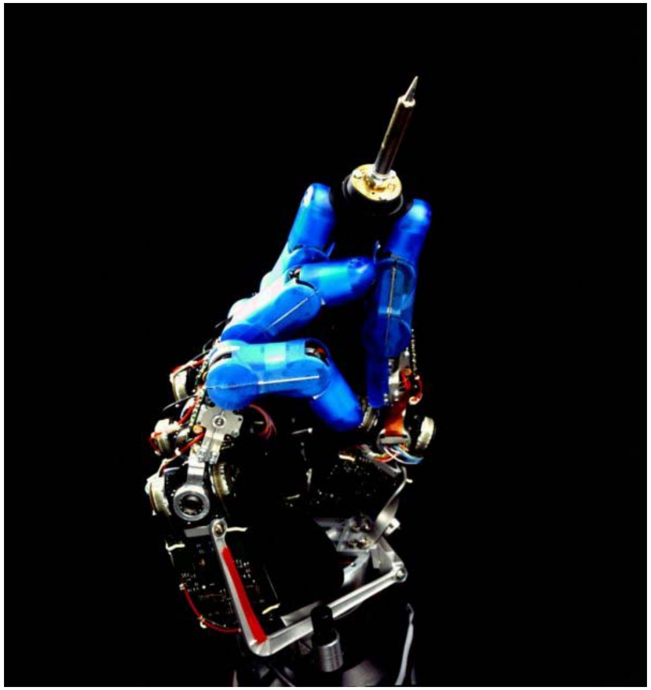
- Tele-operated
- Requires special connectors
- No mobility (although SSRMS has some mobility)

Other Systems

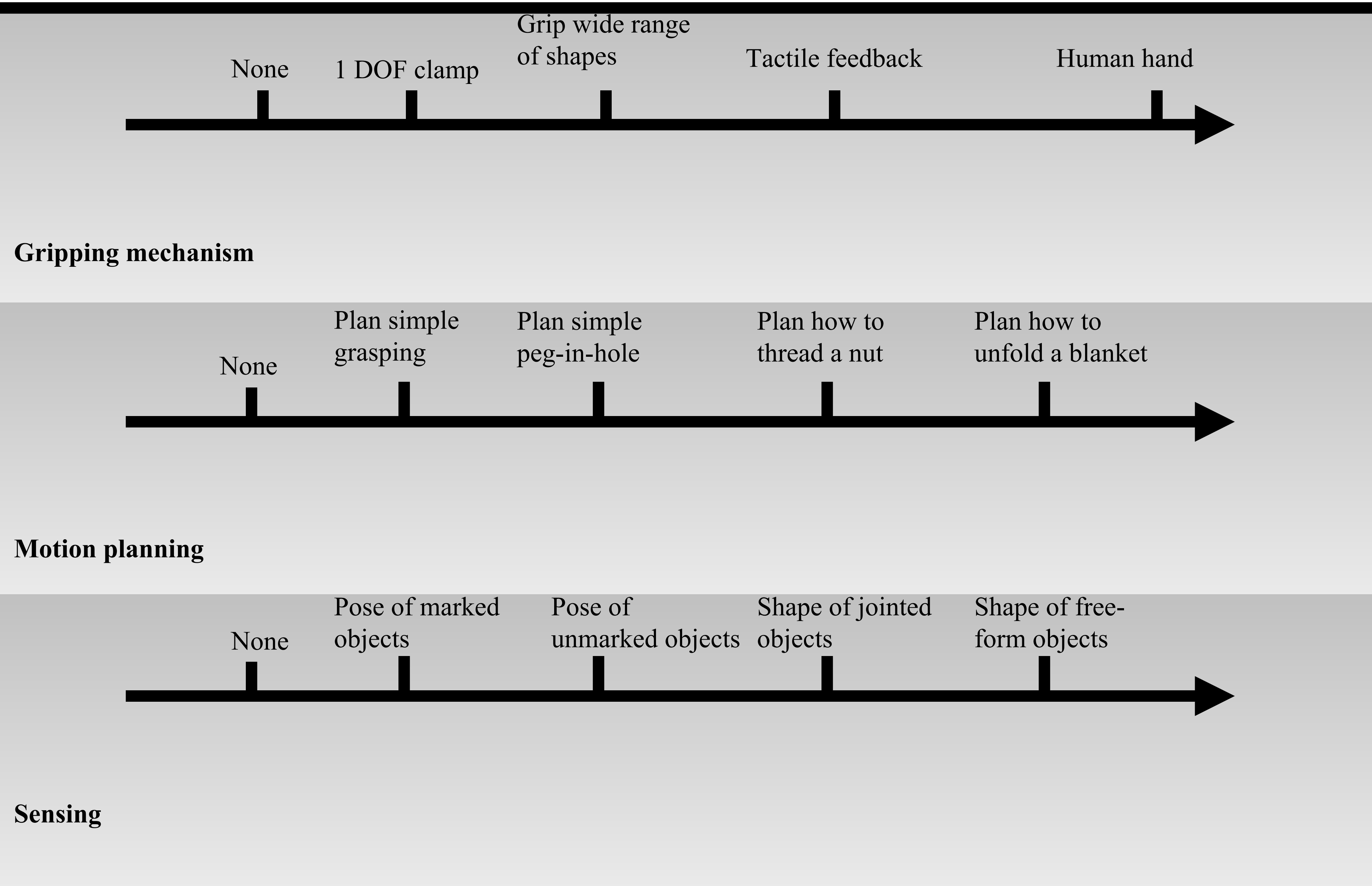
- AERCam IGD
- ASAL
- ETS-VII
- Scamp
- And more…

In-Space Fine Manipulation

- **Grasping objects and acting on them by turning, pushing, pulling, moving or mating.**
- **This consists of:**
  - **Mechanical device (actuator)**
  - **Sensing required to locate, grasp and manipulate**
  - **Control of the actuator**



In-Space Fine Manipulation Metrics

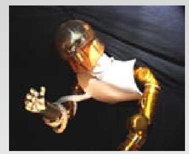


In-Space Fine Manipulation State-of-Art

Gripping mechanism

- None
- 1 DOF clamp
- Grip wide range of shapes
- Tactile feedback
- Human hand

Flight SOA
Shuttle RMS

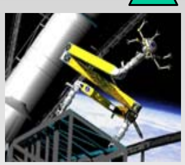


Fielded SOA
Robonaut

Motion planning

- None
- Plan simple grasping
- Plan simple peg-in-hole
- Plan how to thread a nut
- Plan how to unfold a blanket

Flight SOA



Fielded SOA
Skyworker

Sensing

- None
- Pose of marked objects
- Pose of unmarked objects
- Shape of jointed objects
- Shape of free-form objects

Flight SOA
Shuttle RMS
ASVG

Fielded SOA
Skyworker

In-Space Fine Manipulation Relevant Systems

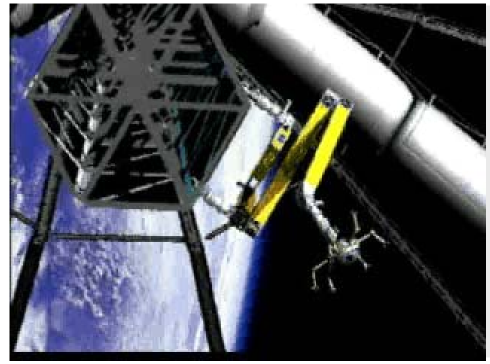
Robonaut

High DOF grippers

Compliant grip

Telepresence interface

Skyworker

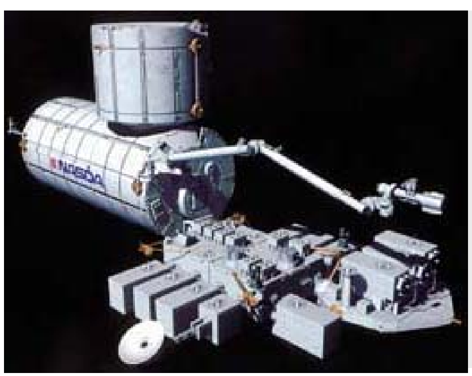


Autonomous visual assembly

Motion planning

Low-energy climb on structure

Japanese Experimental Module RMS



Combines gross and fine manipulation

Performs science experiments in vacuum

Other Systems

- **Special Purpose Dexterous Manipulator (SPDM)**
- **EVA Helper Retriever**
- **Ranger**
- **ROTEX**
- **And more…**

Fine Manipulation

- Qualitative Metrics
  - Autonomy
  - Grasping
  - Manipulating grasped objects
  - Compliance control
  - Trajectory planning
- Quantitative Metrics
  - Degrees of freedom
  - Control rate
  - Energy consumption
  - Minimal graspable object
- Relevant robotic systems
  - Robonaut, Ranger, JEMRMS, SPDM, EVAHR, ROTEX

In-Space Fine Manipulation Claims

Gripping mechanism

- **With minimal support:** Space ready Robonaut hand
- **With strong support:** Ability to use many suited astronaut tools under tele-operation
- ***Breakthrough*:** Naked human hand performance under tele-operation. Suited human hand performance under autonomous control.

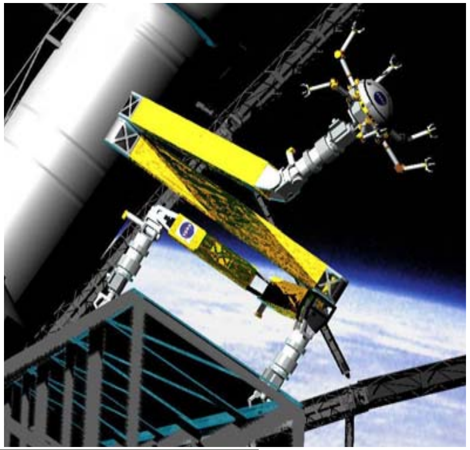
Motion planning

- **With minimal support:** Motion planning for simple assembly peg-in-hole tasks.
- **With strong support:** Operations with complex constraints on gripping and object motion (e.g., turn a nut)
- ***Breakthrough*:** General-purpose autonomous manipulation of free-form objects like blankets and cables

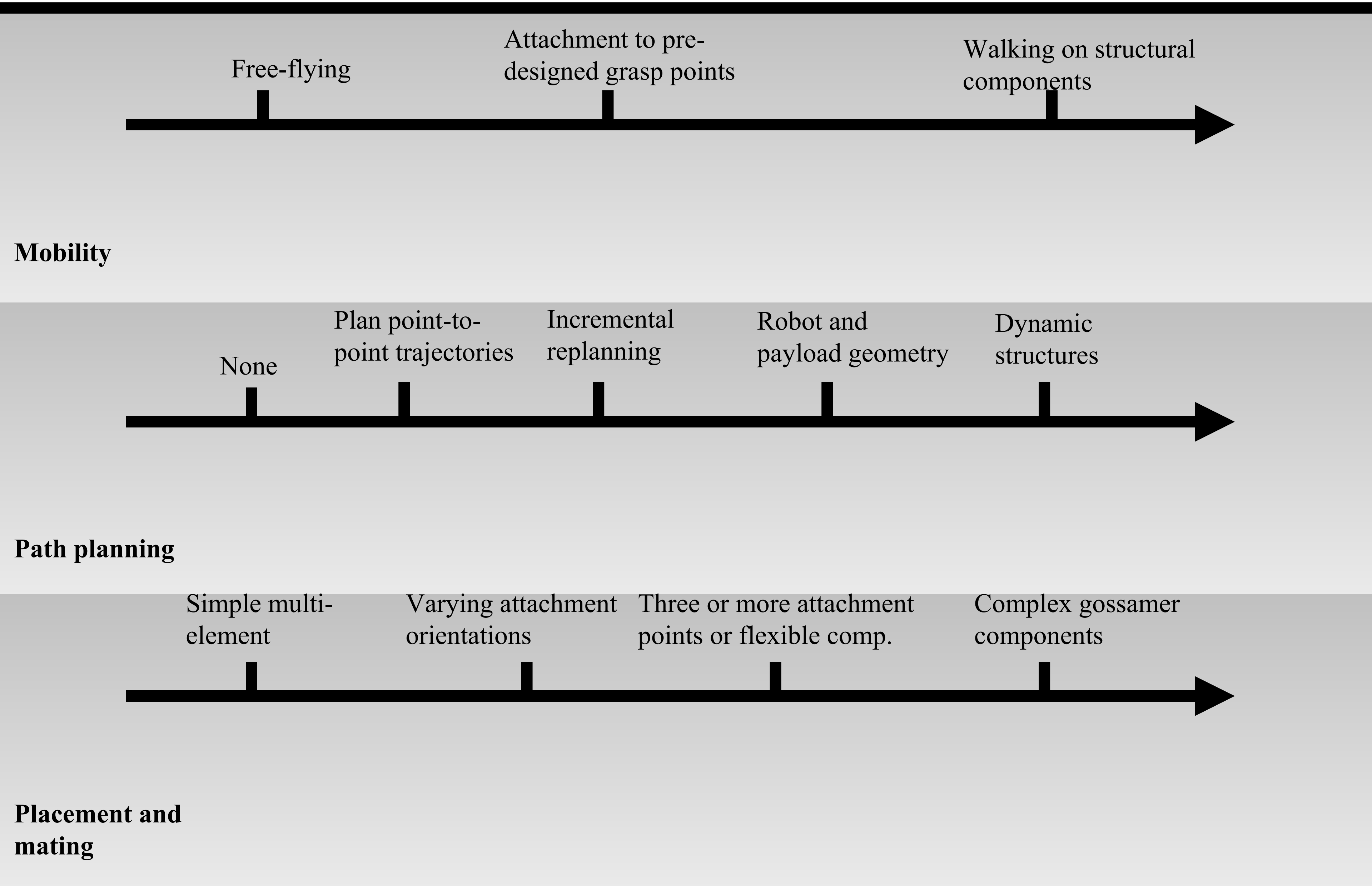
In-Space Mobility and Gross Manipulation

Ability of a robot to move or apply forces to itself and other relatively massive elements.

- Localization, planning and obstacle avoidance
- Efficient locomotion in free-fall:
  - Minimal energy and Δv
  - Minimal torques and forces
- Load transport
- Manipulating large / unwieldy payloads



In-Space Mobility and Gross Manipulation Metrics



In-Space Mobility and Gross Manipulation State-of-Art

Mobility

Free-flying

Attachment to pre-designed grasp points

Walking on structural components

Flight SOA
AERCam Sprint

Flight SOA
SSRMS

Path planning

None

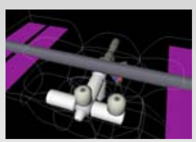
Plan point-to-point trajectories

Incremental replanning

Robot and payload geometry

Dynamic structures

Flight SOA



Fielded SOA
Voronoi Diagrams

Placement and mating

Simple multi-element

Varying attachment orientations

Three or more attachment points or flexible comp.

Complex gossamer components

Flight SOA
Shuttle RMS
w/ crew

Fielded SOA
Skyworker

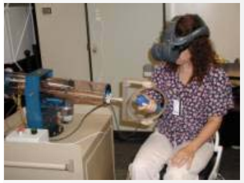
Outline

- Overview/Motivation
- Approach
- Mission Scenarios
- Functionalities
  - Mars Exploration Scenario
  - In-Space Assembly Scenario
  - Projections and Breakthroughs
- Open Questions, Schedule and Future Work

Estimated time capability can be flight-ready, with strong support

	0-5 years	5-10 years	Breakthroughs
Mobility	 100 m autonomous navigation; visual localization	 km scale autonomy; reach several targets per uplink	Autonomous climbing; navigating in confined spaces
	 Access slopes and streambeds	 Deploy tethered cliff explorers	Advanced legged “mountain goat” robots
Science Operations	 Pick up rocks; on-board target selection	Break off rock fragments; on-board data processing	Position microscopes; autonomous site characterization
Robot-Robot Interaction	 Coordinated sensing; sample handoff	 Coordinated assembly and object transport	Dynamic team formation; on-board planning for multiple robots

Estimated time capability can be flight-ready, with NASA investment

0-5 years	5-10 years	Breakthroughs
Mobility and Gross Manipulation		
 Basic motion and object transport	 Climbing on flexible structure; energy-efficient transport	Autonomous coverage patterns; replanning for dynamic obstacles
Fine Manipulation		
 Grip a variety of objects; simple autonomous mating	 Tactile feedback; compliant objects; complex motion planning	 Autonomous manipulation of free-form objects like cables
Human-Robot Interaction		
 Telepresent interfaces; simple voice commands	Gesture recognition; coordinated manipulation with EVA astronaut	Recognition of human goals; high-level dialogue with humans

Outline

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Defining Challenges?

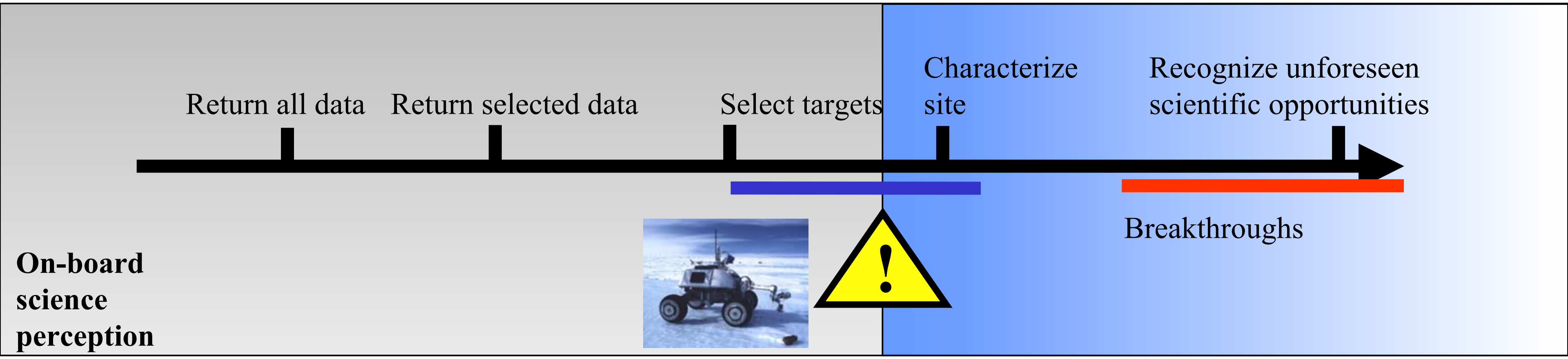
- *Short Term Challenges*
  - Minimal investment insufficient
  - Strong investments achieve desired performance
- *Breakthrough Challenges*
  - Fundamental breakthroughs needed
- Need:
  - ***Minimal investment*** and ***Strong investment*** forecasts
  - Mission scenario desired performance levels

Mission scenario desired performance levels

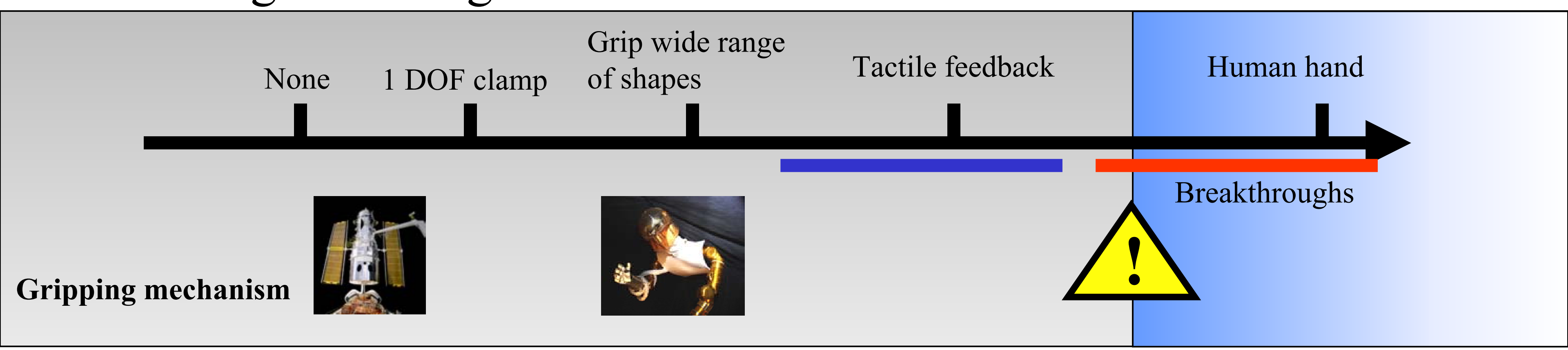
- Touchy subject
- Categories:
  - Mission enabling
  - Mission enhancing (do more without significant cost increase)
  - [Cost cutting]
- 2002 Workshop

Challenges

Short-term challenge:



Breakthrough challenge:



Contributors and Schedule

Schedule/Milestones (1)

CMU Kick-off meeting and site visit	April 25-26, 2001 DONE
JSC site visit	May 3-4, 2001 DONE
Initial contributor solicitations	June 15, 2001 DONE
I-SAIRAS Conference MD Robotics visit	June 18-21, 2001 DONE
JPL site visit	June 22, 2001 DONE

Schedule/Milestones (2)

Maryland SSL, Goddard, NRL and NASA HQ site visit	July, 2001
MIT / Boston site visit	August/September 2001
Brief to CMU	August/September 2001
Interim Report	November/December, 2001

Space Robotics Assessment FY02

- Projections
  - Based on same functionalities and metrics as the state-of-the-art assessment
  - Look for trends in functionality metrics and create performance claims for each functionality
  - Identify requirements for each mission scenario
  - Identify key challenges necessary to perform mission scenarios and develop roadmaps
- Workshop
  - Space robotics roadmap
  - Consolidate community acceptance of report
- Produce video survey of the state-of-the-art in space robotics

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